

THE ELECTRA KrF LASER PROGRAM

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Introduction: In thermonuclear fusion, two light nuclei are combined to produce energy. Fusion is the power source of the Sun. If fusion could be harnessed on Earth, the power plant would have unlimited fuel (the ingredients are deuterium (a hydrogen isotope) and lithium (a plentiful element)), no chemical by-products, and no long-term radioactive waste. The payoffs are so large that numerous scientific institutions worldwide have been working on this problem. However, after almost 50 years the solution is still elusive and challenging. Recently, NRL has spearheaded an approach that appears to be very promising: An array of intense krypton fluoride (KrF) lasers are used to directly compress and heat a small pellet of fuel to the conditions needed for fusion reactions. Experiments and computations at the Naval Research Laboratory show that this approach is scientifically viable and should provide sufficient energy release for a fusion reactor.¹⁻³ However, the present high-power laser used in this research fires twice every hour and requires periodic maintenance. In contrast, a laser for a fusion power plant must fire five times per second for several years and meet stringent cost and efficiency requirements. The Electra Laser Program at NRL will develop a laser that can meet these requirements. Electra will run at 5 Hz with a laser output of 400 to 700 Joules. This will be large enough to develop technologies that can be scalable to the 50 to 150 kJ needed for a fusion power plant beam line.

Components of a KrF Laser: In a KrF laser, electron beams are used to excite the krypton and fluorine. The fundamental laser wavelength is in the ultraviolet at 248 nm. In the mid 1990s, NRL built the Nike laser that demonstrated this process.⁴ Nike can produce more than 5000 J of laser light, with a beam spatial nonuniformity of less than a few tenths of a percent. It is now being routinely used for laser fusion experiments. This outstanding beam uniformity, which is necessary to achieve uniform pellet implosions, plus the relatively low cost and scalability

to power-plant size systems, makes KrF lasers promising for fusion. Figure 1 shows the fundamental laser components. Applying voltage from a pulsed power system to a field emission vacuum diode creates the electron beams. The beams pass through a thin foil that isolates the diode from the high-pressure laser gas. The foil support structure, known as a “hibachi” because of its grill-like shape, is one of our technical challenges. It needs to be highly transparent to the electron beam, yet survive the hostile environment of the laser cell (hydrostatic shock, ultraviolet light, X rays, electrons, fluorine, and HF). The laser needs to have windows with highly transparent antireflective coatings that can also survive this environment and a recirculator to make the gas quiescent before the next shot. Our plan is to perform the research needed to develop these components and then combine them into an integrated system.

Progress in Laser Development: Electra is installed in a newly refurbished 7000 square foot laboratory. Figure 2 shows the new, first-generation, pulsed power system that we have built explicitly for this task. This system uses an array of capacitors that pulse charge a pair of water dielectric electrical transmission lines to 1.2 MV in 3.5 μ s through a 12.1 step-up transformer. The lines are discharged through gas switches into the electron beam diode. We have two such systems. Each produces a 500 kV, 100 kA, 100-ns long electrical pulse five times a second (25 MW), and each can run for up to 100,000 shots before requiring minor (2-hour) refurbishment of the gas switches. This 5-hour duration is unprecedented for a pulsed power system of this size and is more than adequate to develop the initial laser components. We are also developing a more advanced pulsed power system that can meet the ultimate requirements for durability and efficiency. The key component is a new solid-state, four-junction, silicon switch triggered by an integral diode laser. We recently demonstrated this concept with a prototype device. It will eventually replace the existing gas switch technology.

We have designed a hibachi (Fig. 3) for high efficiency and long life. The efficiency is achieved by using an advanced design that eliminates the conventional anode foil and by patterning the beam to miss the hibachi ribs. The latter is more difficult than one would expect because the beam rotates as it propagates from the electron beam emitter to the hibachi. Nevertheless, we have modeled this with three-dimensional particle-in-cell codes and, more importantly, have demonstrated that we can “miss the ribs” experimentally. The same model accurately predicts the electron beam energy deposition in the laser gas. Cooling the hibachi should be achievable by

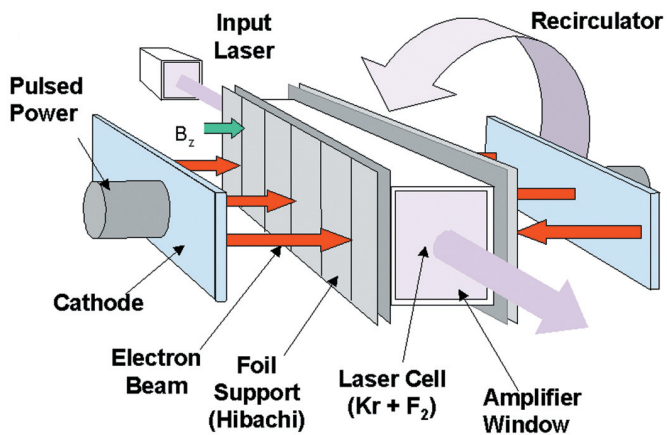


FIGURE 1
Key components of an electron beam pumped KrF laser.

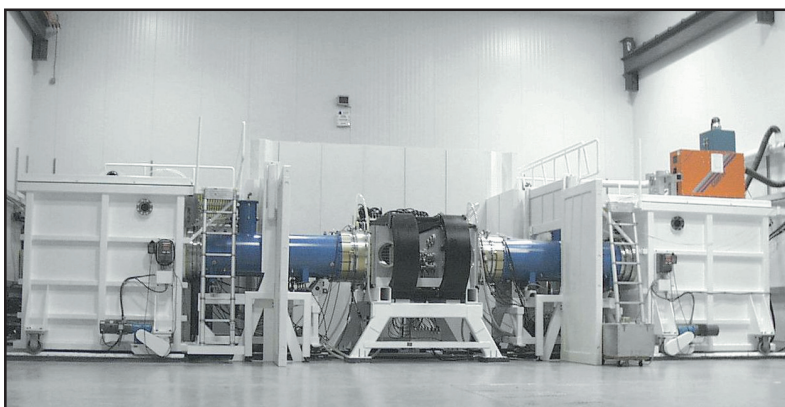
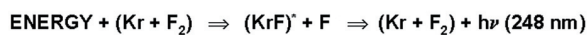


FIGURE 2
The Electra Laser Facility.

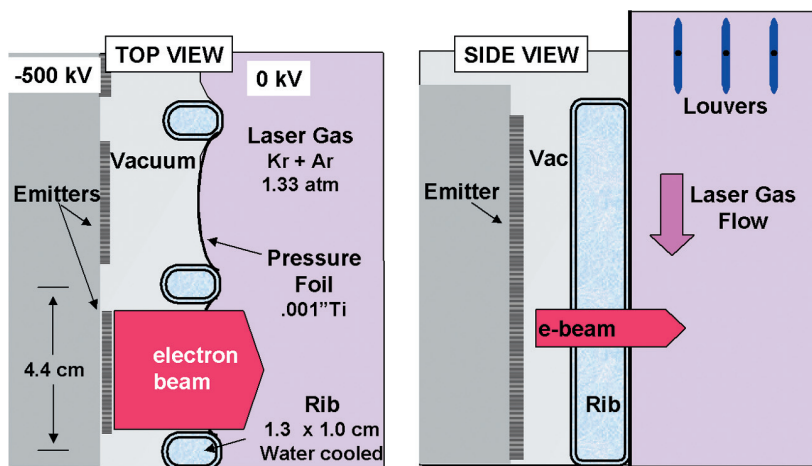


FIGURE 3
Hibachi concept. The louvers are rotated between shots to deflect the gas flow onto the pressure foil.

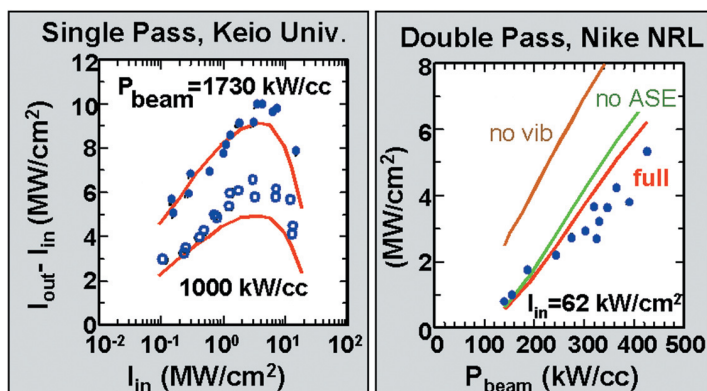


FIGURE 4
Comparison of KrF kinetics code with experiments at Keio University (left) and NRL Nike (right).

momentarily rotating louvers to deflect the laser gas flow to the foil. Our modeling shows that the louvers can be retracted in time to allow the gas to return to a quiescent state before the next shot.

In the arena of KrF physics, we have developed a KrF physics model that features an automated chemistry solver that tracks 24 species, 20 excited KrF states, and 122 reactions. It includes a three-dimensional model of the amplified spontaneous emission. Such sophistication is needed because previous models have been found to be valid over only a limited range of conditions. In contrast, as shown in Fig. 4, our new model can predict the performance of KrF lasers operating under a wide range of conditions.

Summary: Electra is a multifaceted research and development program to develop a KrF laser for fusion energy. The program makes full use of the multidisciplinary technical expertise that is available at NRL. The first-generation pulsed power system has given us a platform to develop the laser components, and we have already made significant advances in the fields of electron beam physics, the hibachi structure, and KrF kinetics. The compact advanced solid-state switch that we have demonstrated has the potential to meet not only the Electra requirements, but also to enable a wide range of Navy applications. We anticipate that we will start operating Electra as a laser sometime in 2002.

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CHARGING AND SHIELDING OF "DUST GRAINS" IN A PLASMA

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Dusty Plasma—a Unique State of Matter:

Plasmas are usually thought of as ionized gases consisting of electrons, positive ions, and neutral molecules. However, "dusty plasmas," which also contain large numbers of particulates, occur in the ionosphere, the Sun's extended corona, comets, the rings of Saturn, fusion devices, and semiconductor processing tools. "Dust grains" in plasma acquire a large negative charge ($\sim 10^4$ electron charges for micron-sized grains) because they are bombarded much more rapidly by the fast electrons than by the slower positive ions. The electrostatic interaction between grains is thus very strong, and the grains can self-organize into crystal structures and liquid-like flows and exhibit phase transitions such as melting. Physicists are excited about this. The grains are large enough and slow enough to follow individually, so that the dynamics of these self-organized states can be observed at a level of detail that is impossible for ordinary condensed matter. Dusty plasma experiments have been mounted all around the world. Dusty plasmas are also of considerable practical importance. For example, dust is thought to be responsible for radar scattering in the D-layer of the ionosphere. In plasmas used for processing, the dust is sometimes a nuisance, but in other cases it can be used to create unique materials.

Charging and Shielding: To understand the interaction between grains, it is first necessary to determine the charge that the grains acquire. It is also important to understand how the electrostatic field

around a grain is shielded by the nearby plasma, i.e., the negative grain attracts a preponderance of positive ions, causing the electric field to fall off faster than the $1/r^2$ law that governs in vacuum. The scale length for this shielding is known as the Debye length λ_D . Charging and shielding of a small object in a plasma are among the oldest problems of plasma physics. The original work was done by Nobel-prize chemist Irving Langmuir¹ in 1926, and famous papers building on Langmuir's work have appeared in every subsequent decade. Could there be any surprises in an area that is so well-worked? The answer turns out to be yes. The "orbital-motion-limited" theory developed by Langmuir and his successors is based on the idea that the ions and electrons near a grain at any moment are particles that come from far away in the ambient plasma, fly by the grain and back out to the ambient plasma, or else strike the grain and are absorbed (Fig. 5). The collision mean-free-path λ_{mfp} for these plasma particles is very long compared to λ_D , so it was natural to neglect collisions. However, in 1959, Ira Bernstein² pointed out that a positive ion can lose most of its energy in a collision, and then be unable to escape from the negative potential well around a grain. He speculated that these "trapped ions" could be important, even if collisions were infrequent, but nonetheless neglected collisions "in order to obtain a tractable problem." In the subsequent 40 years, this comment was often repeated, but all published theories still neglected collisions and trapped ions. However, in the last year we succeeded in finding an exact analytic solution including collisions and trapped ions.³ We showed that collisions may be rare, but each trapped ion stays trapped for a very long time; consequently, the trapped ion density steadily builds up and becomes dominant (Fig. 6). A trapped ion can be lost only via another collision. Since both the creation rate and the loss rate of trapped ions are proportional to the collision frequency ν , the steady state density of trapped ions is independent of ν . Hence, the paradoxical conclusion that in steady state, collisional effects dominate—even in the limit of zero collision frequency! (The resolution is that the time to establish steady state is inversely proportional to ν , so if ν is truly zero, steady state is never reached. But for practical values of ν , steady state is in fact reached very quickly.) We also find that there is typically a very large flux of trapped ions to the grain. Even when the mean free path is $\sim 50\lambda_D$, this reduces the negative charge on the grain by about a factor of two (Fig. 7).

What's Next?: Amazingly enough, in the 75 years since Langmuir's work, no experiment was done looking for trapped ions. However, in the last few

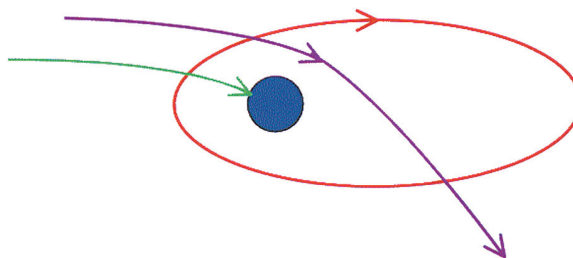


FIGURE 5

According to orbital-motion-limited theory, ions fly in from the ambient plasma and either miss the grain and fly back out to the ambient plasma (purple orbit), or hit the grain and stick (green orbit). Our theory also includes trapped ions (red orbit) created by collisions.

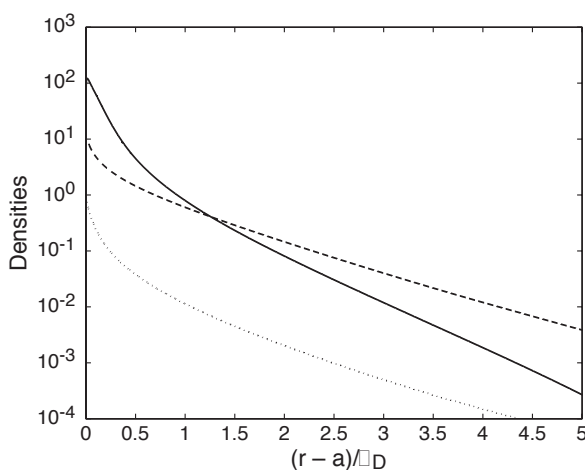


FIGURE 6

Trapped ion density (solid curve), deviation of untrapped ion density from ambient (dashed curve), and deviation of electron density from ambient (dotted curve). All densities are scaled to the ambient density n_0 . Note that the trapped ion density near the grain is $100 n_0$, and is ten times larger than the untrapped ion density.

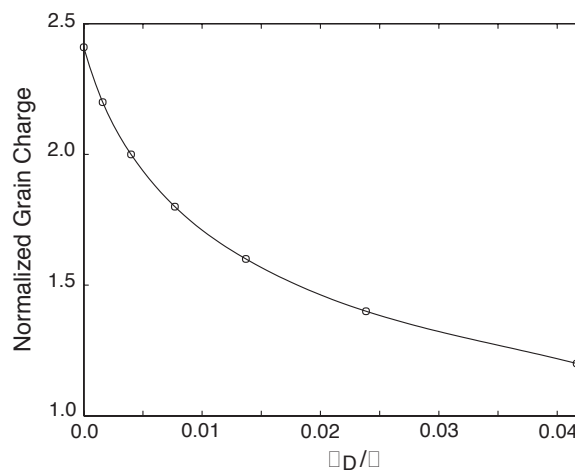


FIGURE 7

Grain charge (in normalized units) as a function of λ_D/λ , where λ is the mean free path and λ_D is the Debye screening length.

months, Scott Robertson and collaborators at the University of Colorado have done such an experiment,⁴ and the initial results appear to support our theory. It will be necessary to reinterpret recent measurements of dust grain charge, since we now understand that the fields applied to measure the charge act on both the grain and its surrounding cloud of trapped ions. We and many others are applying our new understanding of the field surrounding each dust grain to studies of the overall dynamics and self-organization of dusty plasmas containing many grains. There are also applications to spacecraft charging by surrounding plasma and to the interpretation of Langmuir probes, one of the basic plasma diagnostic techniques.

[Sponsored by ONR and NASA]

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AN ELECTRODELESS MOLY-OXIDE DISCHARGE FOR LIGHTING APPLICATIONS

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Introduction: Lighting consumes 23% of the electrical energy in commercial, industrial, and military buildings. Thus there is a large potential for savings by improving lighting sources for general illumination. The efficiency of a light source for illumination, termed the efficacy, is measured in visible lumens per watt (lpw) of input electrical power. For example, the incandescent filament bulb of the Edison design has an efficacy of only ~15 lpw, the standard fluorescent tube ~70 lpw, and metal halide lamps ~100 lpw. In addition to efficiency, the ideal light source should also provide a broad emission spectrum throughout the visible region in order to produce a high quality of color rendition. A third criterion is the stability of the source output over a long lifetime to minimize operational and replacement costs. The fourth criteria of an ideal lamp, and the most chal-

lenging, is the future requirement of environmental safety. Both fluorescent tubes and metal halide lamps contain mercury (Hg), and on Navy vessels, Hg is already treated as a hazardous material. No existing commercial light source is optimal in all four criteria. In an effort to develop the ideal light source, NRL is investigating mercury-free, electrodeless, molybdenum-oxide (MoO₃) plasma discharges for use in lighting applications.¹

Operation of the Moly-oxide Lamp: As a lighting source, the moly-oxide discharge requires a multidisciplinary approach combining quartz fabrication, radio frequency (RF) electronics, plasma physics, oxide chemistry, and atomic excitation physics. The experiments are performed with specially designed quartz bulbs that contain a charge of MoO₃ as powder and an argon (Ar) buffer between 0.5 and 8 Torr. A plasma discharge is initiated in the Ar buffer via an external spiral coil driven by a 13.56 MHz RF generator. An electronic matching circuit, similar to the ballast in a fluorescent light, allows efficient transfer of the RF energy into the plasma. This RF coupling approach provides a long lifetime system because there are no internal electrodes to undergo plasma degradation. The resistivity of the partially ionized Ar leads to heating of the gas and walls of the bulb. As a pure metal, molybdenum (Mo) will not vaporize below the annealing temperature of quartz (1400 K); however, MoO₃ has a high vapor pressure of 1 Torr at 1007 K. Thus the moly-oxide undergoes a sudden evaporation from the quartz walls as they heat up to these temperatures. Once MoO₃ diffuses into the plasma ring, kinetic reactions dissociate it, and the Mo atom is subsequently excited by electron collisions to radiate in the near-UV region and throughout the visible domain. This process is similar to metal halide lamps except that oxygen takes the place of the halide in the metal recycling process and Hg is not used to produce a high-pressure, equilibrium plasma.

Figure 8 presents an absolutely calibrated spectrum of the moly-oxide discharge. The photopic curve represents the relative sensitivity of the eye to various wavelengths. Some of the prominent atomic lines in the spectrum are denoted in the figure, and one can see the strong 550 nm emission from Mo at the peak of the photopic curve. The broadband continuum underlying the lines throughout the visible region comprises the white light emission and provides good color rendition. The efficacy of the present design is ~40 lpw. Improvements to the discharge as a general lighting source will require a reduction of the near-UV feature by shifting the energy into visible wavelengths.

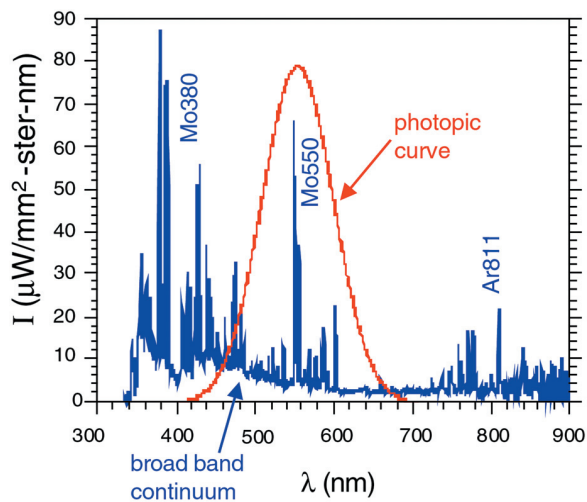


FIGURE 8
Calibrated spectrum from a moly-oxide electrodeless discharge with an Ar buffer. The photopic curve is the eye sensitivity.

FIGURE 9
Experimental configuration showing the moly-oxide bulb discharge in the center driven by an RF excitation coil with several diagnostics.

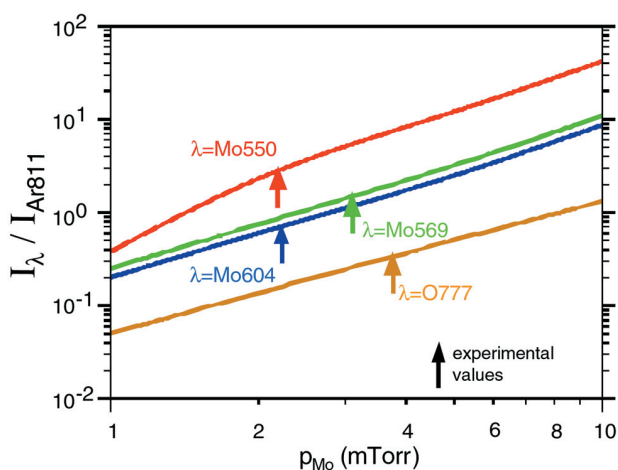
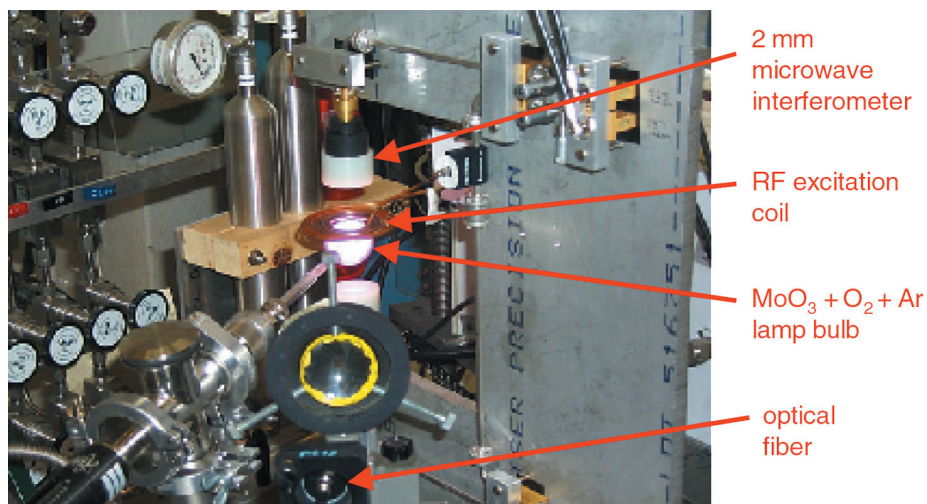


FIGURE 10
Ratio of line emission intensities from Mo and O with Ar as a function of the Mo partial pressure. Solid lines are from numerical simulations; the arrows indicate experimental data.

Mo partial pressure: The key to improvements for lighting applications is an understanding of the properties of the discharge, which is accomplished through a combination of diagnostics and modeling analysis.² Figure 9 shows the experimental setup. To highlight one result, the ratio of emission line intensities between Mo and Ar in conjunction with a Boltzmann model for the electron distribution function can be used to obtain the partial pressure of Mo atoms in the discharge. Figure 10 gives the results from spectroscopic analysis and simulations. The existing experiments indicate a Mo partial pressure of 2 to 4 Torr, but a significant enhancement of the 550-nm Mo emission, and correspondingly the efficacy, can be expected as the Mo pressure is doubled. This effect is due to the optical trapping of the UV resonance lines in Mo and the subsequent increase in visible emissions from untrapped levels.

Summary: The moly-oxide lamp is designed to combine the optimal properties of existing lighting

systems, namely, the high efficacy, broadband white light emission found in high-pressure metal halide discharges and the long lifetime of the new low-pressure Hg fluorescent lamps driven by electrodeless RF coupling, such as the Philips Q-lamp. The objective of addressing these goals without the use of environmentally hazardous materials places the program at the leading edge of lighting research.

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